Dynamic sensation of comfort in buildings: the temperature changes effects

M. Palme, A. Isalgué, H. Coch, R. Serra
Universitat Politècnica de Catalunya, ETSAB, Spain

I. Marincic
Universidad de Sonora, Mexico

A. Fanchiotti
Università di Roma Tre, Italy

ABSTRACT

The sensation of comfort in buildings depends on external and internal variables: the well-known PMV method relates the expected temperature with the physiological behavior of the human body. Some models have discussed the relevance of adaptation factors, in order to explain the higher expected "good" temperature of users living in warm climates. The same PMV method has been modified for these climatic situations. An adaptation term has clearly to be considered, but other effects are important to determine the real expected temperature. In this paper temperature changes are considered to play an important role determining the expected "good" temperature. Effects of ventilation, rapid thermal changes when people move inside or outside of a building, continuous change in the temperature rate in the HVAC controlled spaces, are investigated here.
Results show how to determine a dT/dt dependent term, which has to be considering in the PMV evaluation, in warm as in temperate climate. These results will be compared with field studies for different climates. A PID (proportional integrative derivative) correction in the PMV predict results seem to have to be expected, to consider at the same time adaptation and temperature rate effects.

1. INTRODUCTION

The thermal comfort evaluation is an important need in architectural project and in HVAC system design. Different methodologies were developed in the past half of century, in order to approach the evaluation of comfort, but the more complete appears the method that utilize a thermal balance for the human body. The exact solution of the balance equation is complicated to obtain, but Fanger (1970) propose the values of the internal variables "skin temperature" and "heat loss by evaporation of sweat secretion" that lead to a comfortable sensation. With these values is possible to evaluate the thermal charge of the body, and the consequent comfort perception. The PMV method is now the best method proposed for the thermal comfort evaluations, because of his generality (all the variables are considered) and of the good accord with the field studies conducted in USA and Denmark by the author. However, a lot of problems in the application of the PMV theory are open today. The influence of the climate over the concordance of the results obtained from the PMV analysis with the field studies is a reality. In the recent past some authors have discussed the relevance of the climate over the results, and the possible ways to complete the Fanger's equations with an acclimatization term. In Europe, Van Hoof and Hensen (2005) discuss the relevance of the acclimatization factor in temperate climate. In Mexico, Marincic, Ochoa and Isalgué (2005) propose a correction for the ACT program (a program for the evaluation of comfort based on the PMV method), in order to consider the acclimatization. The same Fanger discuss the possibility of correct the PMV in some climates (Fanger, 2002).
The importance of the acclimatization is really large, but other factors may influence the results of a PMV analysis. Particularly, the presence of a fast change in the external temperature or in the heat exchange of the body, can generate a strong discomfort sensation, that has not been fully evaluated. In this work the eventual addition of a "fast temperature change" term in the Fanger's equations is discussed. The results obtained with the model are compared with field studies conducted in tree countries: Spain, Mexico and Italy.

2. METHODOLOGY

2.1 Overview

Considering the transition from one space into another, it is possible that the physiological response of the body assumes different forms. Particularly, when the transition crosses the zero PMV line, it is possible to feel an overheating or an overcooling sensation. Otherwise, thermal mass of the body can cause a delay in perception of the new situation. Psychological and cultural factors also play an important role. For example, if the start situation locates in a +2 PMV and the final situation locates in a –1 PMV, people can feel a strong cold sensation in the first minutes of the transition and vote –2, or can feel a relief sensation and vote 0.In order to determine the real behavior of people, field studies have to be conducted. The relief sensation has probably a psychological origin, but a completely physiological definition of the transition is very difficult to obtain, due to the presence of expectations conditioning. Expected results are the choice between a gradual passage into the second environment and an overheating or an overcooling sensation. A psychological relief sensation can also to be expected. Figure 1 shows the possible characteristic of a gradual passage, Figure 2 shows the characteristic of an overcooling. Figure 3 shows the relief sensation and corresponding votes.

2.2 PMV calculation

The Fanger's method starts from the heat balance of the body expressed in equation (1):

$$H - E_d - E_{sw} - E_{re} - L - K = S \quad (1)$$

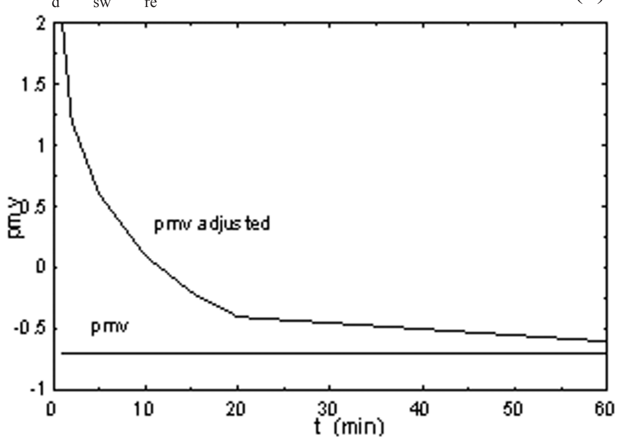

Figure 1: gradual passage from pmv 2 to pmv -0.7

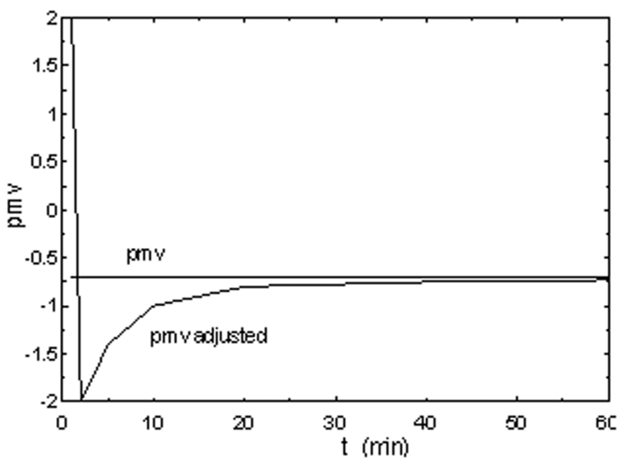

Figure 2: overcooling sensation passing from pmv 2 to pmv -0.7

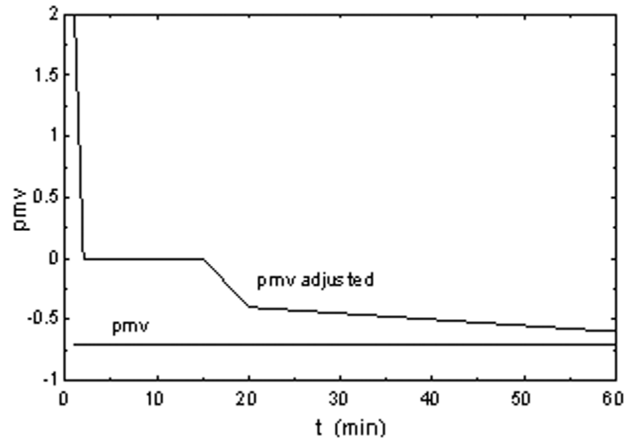

Figure 3: relief sensation during transition from pmv 2 to pmv -0.7

were:

H: internal heat production in the human body

E_d: heat loss by water vapour diffusion through the skin

E_{sw}: heat loss by evaporation of sweat from the surface of the skin

E_{re}: respiration latent heat loss

L: respiration sensible heat loss

K: heat transfer from the skin to the outer surface of the clothed body

S: energy that the human body would have to loose or receive in the unit time to keep the energy balance while feeling comfortable, that is, assuming for the skin temperature and for E_{sw} the comfort values.

The value S is directly connected with the PMV (Predicted Mean Vote) concept (Fanger, 1970) expressed in equation (2):

$$PMV = \left(0.352 e^{-0.042 \frac{M}{A_{Du}}} + 0.032\right) S \quad (2)$$

were:

S: result of equation (1) in comfort conditions

M: metabolic power of the body. The difference between M and H is that M is the total power production of the metabolism, where H is the heat production of the metabolism, the difference being mechanical work done by the body.

A_{Du}:surface of the human body

In dynamical conditions, the value S has to be changed for a new value S':

$$\| S' \| = \| S \| + \left\| \frac{\delta S}{\delta t} \right\| \Delta \quad (3)$$

were Δ is an empiric coefficient (time dimension). A positive value would mean an overestimation of any change, and a negative value, a tracking effect, smoothing fast changes.

With this new value is possible to predict a dynamical transition vote. Evaluation of PMV and adjusted PMV with the new S value was made with the EES software. The coefficient Δ has to be obtained from field studies, fitting the empiric results always with the EES software. More difficult appears to determine the sign of the new S term, as it might depend on the previous PMV, and the same concordance of sign between S and its variation is not secure, as it might also depend on the previous S or PMV.

2.3 Experimental conditions

As first experiment, the dynamical transition from the external situations resumed in Table 1 (Rome), 2 (Hermosillo) and 3 (Barcelona) to the internal situation resumed in Table 4 and Table 5, was evaluated.

Table 1: external conditions in Rome on 17/05/2007, 13.00 h. Ta: air temperature, Tmr: mean radiant temperature, v air: speed of air movement, rh: relative humidity, Met: estimated metabolism of the subjects, Clo: average dressing of people.

Ta (°C)	Tmr (°C)	v air (m/s)	rh (%)	Met	Clo
23	24	0,5	50	1,0	0,66

Table 2 : external conditions in Hermosillo on 10/05/2007, 12.00 h.

Ta (°C)	Tmr (°C)	v air (m/s)	rh (%)	Met	Clo
32	33	0,3	15	1,0	0,66

Table 3 : external conditions in Barcelona on 17/05/2007, 12.00 h.

Ta (°C)	Tmr (°C)	v air (m/s)	rh (%)	Met	Clo
23	24	0,5	50	1,0	0,66

Table 4 : internal conditions in Rome and Barcelona

Ta (°C)	Tmr (°C)	v air (m/s)	rh (%)	Met	Clo
20	21	0,2	40	1,0	0,66

Table 5: internal conditions in Hermosillo

Ta (°C)	Tmr (°C)	v air (m/s)	rh (%)	Met	Clo
23	24	0,2	30	1,0	0,66

Internal conditions differences between Mexico and Europe makes the results more comparative, due to the different adaptation of people living in the Sonora desert, that feel comfort in a different range of temperatures, displaced to high values.

The experiment was conducted with students 20-25 years old, divided in two groups. First all students voted outside, then one group moved inside. Past 20 minutes, the second group moved inside and immediately all students voted. They voted every minute during 15 minutes, and every 5 minutes during other 45 minutes.

Clo values were estimated according to D'Ambrosio, Fato, Piccininni, Alfano and Cirillo (1986). Met values were estimated according to Fanger (1970).

All the environmental parameters were registered during the experiment with Babuc and Escort systems. Type of experiment has also to be considered as Class II, according to De Dear classification (De Dear, 1998).

3. RESULTS

Figures 4, 5 and 6 show the votes of students in the tree experiments. It has to be noted that the internal conditions were not completely stable (Figs. 7-9), so the relation between the first and the second group is the fundament parameter of the analysis.

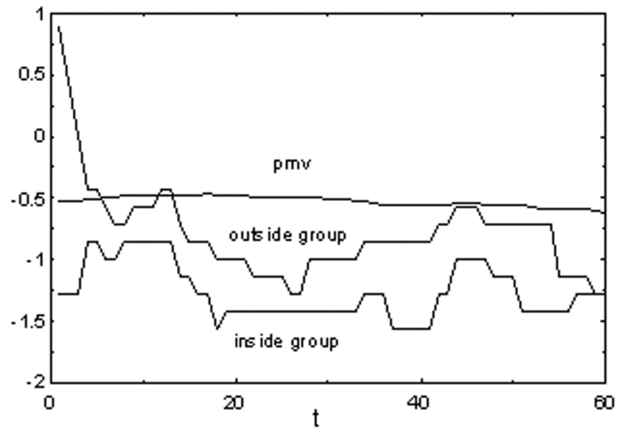

Figure 4: pmv and real votes in Hermosillo, as a function of time.

Results for PMV are something lower than the predicted votes, due probably to a low estimation of the increase in the metabolic rate during the transition. In the present case, it seems that long time in a "cold" ambient leads to an overestimation of cold sensation (Barcelona and El Hermosillo values) in most situations. In Rome, the evolution of temperature with time might influence further and avoid seeing this effect.

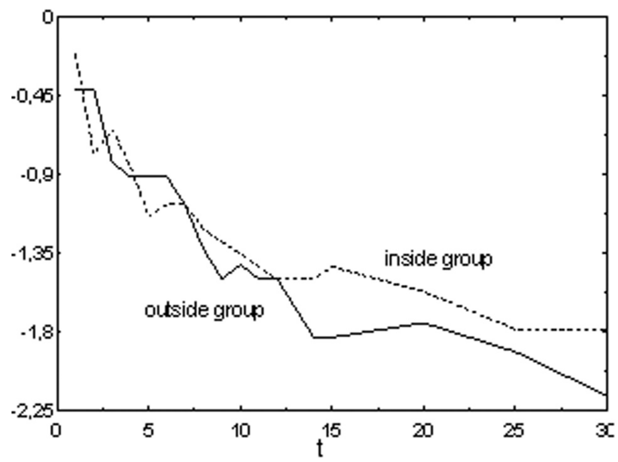

Figure 5: real votes in Rome, as a function of time

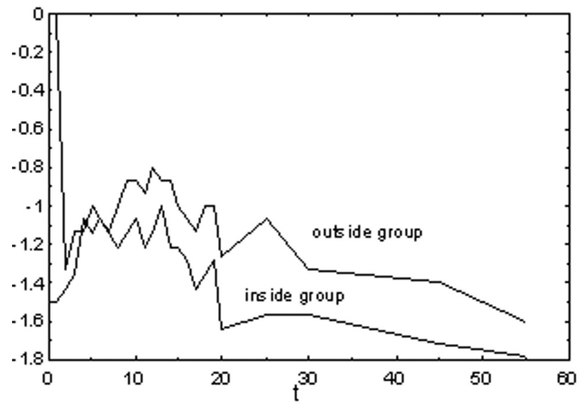

Figure 6: real votes in Barcelona, as a function of time

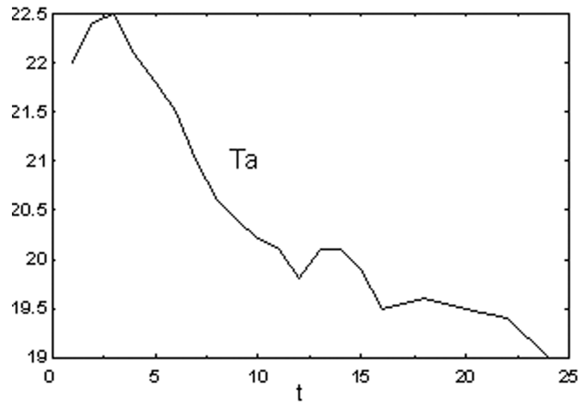

Figure 7: internal temperature variation in Rome

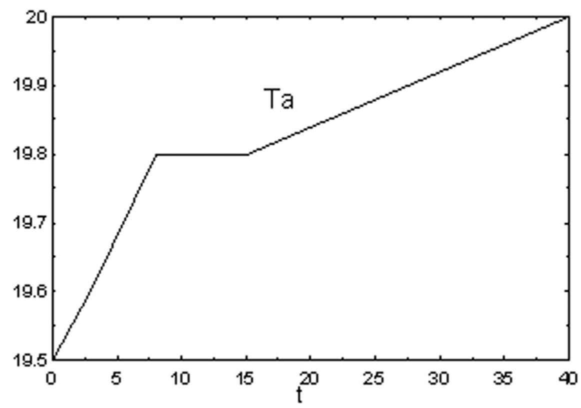

Figure 8: internal temperature variation in Barcelona

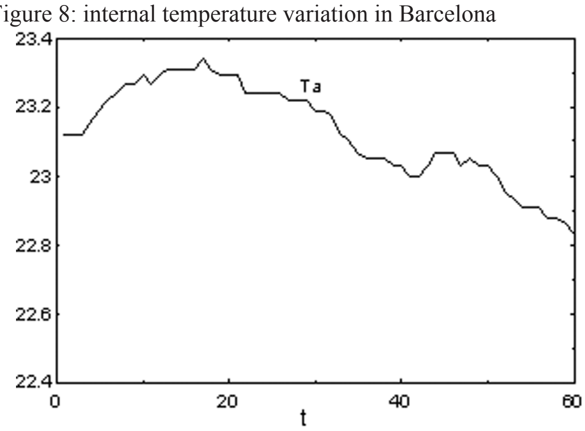

Figure 9: internal temperature variation in Hermosillo

The influence of entering in a new environment might be different in the different cases studied, because of different conditions. Also, the 20 min in exterior conditions might be insufficient in some cases, but this time was chosen as a compromise to avoid excessive exterior changes, and to avoid also boring the people involved.
Probably the thermal mass of the body, with the delay that causes on the perception of the new conditions, plays the more important role in our experiments. It seems that a large time adaptation (more than one hour) could be present. Comparison between Mexican and Europe students shows the existence of an adaptation important correction. The expectation factor is fixed for the Sonora desert at 1.6, extending the Fanger (2002) results for the hot sensation to the cold case.

4. DISCUSSION

The first objective of this work was the estimation of the Δ coefficient. It was made fitting the experimental curve with the EES software. This operation had two parts: first the temporal dependence (due to variations in the HVAC system control) of the thermal charge S present in the internal environment was substituted with the average value, and second the dynamical coefficient was evaluated in dependence from the static vote of the internal group, assumed as reference for the second group. The form selected to fit the curve was:

$$pmv = (0.352e^{M/Adu} + 0.032)S \tag{4}$$

to evaluate the first time dependence, and

$$pmv = (0.352e^{M/Adu} + 0.032)[S + (S - Sp)\Delta/t] \tag{5}$$

to determine the coefficient Δ.
Empirical values of S, Sp and Δ calculated are resumed in Table 6.

Table 6: empirical values of S, Sp and Δ

	S (W)	Sp (W)	Δ (s)
Rome	-9.45	10	-21
Barcelona	-9.30	10	-22
Hermosillo	-5.20	30	-20

The negative value of the coefficient means a "smoothing" or tracking effect. This might be interpreted as the effects of the delay caused by the thermal mass of the body. However, it is a common idea that, in some cases, to enter in a cold environment coming from a very hot one may lead to an "under cooling" sensation. This is not observed here, but more experiments have to be done, with different values of the change of solicitation S-Sp.

5. FUTURE PERSPECTIVES

The obtained results show that, in the considered cases, the most important thing in considering the time variations is the "smoothing" which manifest in the first 20 minutes in the new environment. Due to the conditions present, we think that more experiments have to be done. Transitions from cold to warm have also to be studied, for various differences of temperature. A further task will be the comparison between the Fanger's method and others methods like ACT in dynamical situations. Normally, adaptive methods are based on the difference between an equivalent temperature (dependent on the parameters of the environment) and a desired temperature (dependent on the factors of the perception, including expectations). This fact permit to adjust the difference between the two temperatures by adding an average term, which takes in account the adaptation, directly related with the yearly or monthly average temperature. PMV is calculated in ACT by equation (6)

$$PMV = 3\tanh\frac{T_e - T_d}{4} \tag{6}$$

were:

Te = equivalent temperature sensed by users

Td = desired temperature of the users

Taking into account the dynamical transition and also the adaptation, it is possible to propose the form of a PID (proportional integrative derivative) processor for the total complex behavior of the human body.

So, the proposed equations can be

$$\| S' \| = \| S \| - I\int_1^n \| S dt \| + \Delta \left\| \frac{\delta S}{\delta t'} \right\| \tag{7}$$

for the Fanger's adjusted method, and

$$\|T_e' - T_d'\| = \|T_e - T_d\| - i\int_1^n \|T_e - T_d\| dt + $$

$$+ d \left\| \frac{\delta(T_e - T_d)}{\delta t'} \right\| \tag{8}$$

for the adaptive adjusted methods.

Comparison between PMV obtained from adaptive and PMV obtained from Fanger's adjusted methods will shows the goodness of the adaptive approach, which is clearly less rigorous (in physical sense) than the balance approach of Fanger.

6. CONCLUSION

Field studies over the comfort sensation are an important verification of the ideas that were developed in the numerous investigations on human relation with the environment. Dynamical evaluations require also a very large number of experiments, which have just started. Only when a large database is obtained, it would be possible a really critical discussion over the questions related. In this way authors program to work continuously on the themes opened with this first approach. As a final conclusion, it is possible to say that people vote under a lot of conditions and conditioning, with differences from the actual prediction obtainable from the theories. Separate physical phenomena and psychological expectation in order to understand how the different factors influence the perception is also an important need, in times of energy savings attention and comfort request.

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